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A COMPUTATIONAL BLAST VALVE STUDY

Dixie M. Hisley

February 1985

US ARMY BALLISTIC RESEARCH LABORATORY
ABERDEEN PROVING GROUND, MARYLAND

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Blast Valve	Maximum Shock Velocity	Computational Modeling
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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The BRL Q1D code was modified to include a diaphragm blast valve model. The diaphragm/blast valve model was verified and used to computationally determine the suitability of using a fast-acting (blast) valve to replace diaphragm-breaking as the means of initiation flow in a large shock. For a 1-dimensional model of the Centre d'Etudes de Gramat shock tube, it was determined that a blast valve which opens in less than 50 milliseconds approximated shocks within the following limitations: a) peak overpressure was within 15% of its final value; b) time of arrival of peak was within 15% of its final value;

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c) rise time of the incident shock was increased no more than 8 ms over the rise time computed for the instantaneous blast valve opening.

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I. INTRODUCTION

The general objective of this blast valve study is to determine, through computational modeling, the suitability of using a fast-acting (blast) valve to replace diaphragm-breaking as the means of initiating flow in a large shock tube. In conventional shock tubes, a diaphragm of thin fragile plastic or metal sheet is normally used to separate the driver gas from the driven gas. However, a fast-acting valve has distinct advantages over a diaphragm, and operationally performs the same role.

With regard to the diaphragm shock tube, problems include (a) time consumptive preparation, installation, and replacement of the diaphragms, (b) the possibility of diaphragm fragments and residue interfering with desired flow conditions or damaging models, and (c) the need for artifical bursting techniques (piercers, explosive charges, etc.) to initiate flow at some starting conditions. The number of cycles a diaphragm shock tube can be operated per day decreases as the size of the diaphragm increases and with added complications such as artificial bursting techniques.

Conversely, the fast-acting valve has none of these problems. As reported by Sverdrup,[1] two fast-acting sliding sleeve valves Sverdrup designed (12 and 16 inches in diameter) were used "hundreds of cycles without significant maintenance often 8 to 15 cycles per day." An additional advantage of the fast-acting valve if appropriately designed and constructed, is its ability to not only start, but stop, and regulate shock tube flow for a wide range of operating conditions. The capability to regulate shock tube flow implies that the blast valve's open area versus time is a variable that can be altered to produce many desired waveshapes.

The main operational role of the blast valve or the diaphragm is to initiate shock tube flow either by bursting (diaphragm) or by mechanically opening (blast valve). The opening times of diaphragms are typically much shorter than the opening times of blast valves. These opening times are important because the accelerating phase of the subsequent shock wave motion has been attributed to the finite time required for the diaphragm, or by

[1]Private Communication from Dr. Fritz Oertel, Ballistic Research Laboratory, May 1983.

analogy for the blast valve, to open fully.[2-5] That is, the opening time of either mechanism directly affects the distance required for the shock wave to reach its maximum velocity. As the opening time increases, the distance to shock formation (defined as attainment of maximum shock velocity) increases. Thus a possible disadvantage of blast valves is that they require longer distances to achieve shock formation than diaphragms.

As mentioned earlier, the goal of the remainder of this report is a determination of the suitability of a fast-acting (blast) valve to replace diaphragm breaking in a large shock tube. The preceding will be achieved by (1) validation of a computational diaphragm/blast valve model with experimental results and (2) utilization of the computational diaphragm/blast valve model with a large shock tube to determine if acceptable shock formation distances can be obtained for various blast valve opening times and critical operating conditions.

II. APPROACH

This section describes the two phases of this study; a) validation of a computational blast valve model with experimental results for a conventional shock tube and b) a one-dimensional (1-D) computational study of blast valve suitability for the large shock tube at the Centre d'Etudes de Gramat, France.

A. Validation of a Computational Blast Valve Model

One of the basic research efforts at the Ballistic Research Laboratory (BRL) is to computationally model shock tube processes. The BRL quasi-one-dimensional (Q1D) code is an adiabatic, inviscid Eulerian computer algorithm adapted by BRL for this purpose. A good description of the BRL Q1D computer algorithm was reported by Coulter, Bulmash and Kingery[6] and will be repeated here for completeness.

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[2] C.J.S.M. Simpson, T.R.D. Chandler, and K.B. Bridgman, "Effect on Shock Trajectory of the Opening Time of Diaphragms in a Shock Tube," Phys. Fluids, Vol. 10, No. 9, September 1967, pp. 1894-1896.

[3] E.M. Rothkopf and W. Low, "Diaphragm Opening Process in Shock Tubes," Phys. Fluids, Vol. 17, No. 6, June 1974, pp. 1169-1172.

[4] F.L. Curzon and M.G.R. Phillips, "Low Attenuation Shock Tube: Driving Mechanism and Diaphragm Characteristics," Canadian Journal of Physics, Vol. 49, 1982, pp. 1982-1993.

[5] Takefumi Ikui and Kazuyasu Matsuo, "Investigations of the Aerodynamic Characteristics of the Shock Tubes," Bull. JSME., Vol. 12, No. 52, 1969, pp. 774-782.

[6] G.A. Coulter, G. Bulmarsh, and C.N. Kingery, "Experimental and Computational Modeling of Rarefaction Wave Eliminators Suitable for the BRL 2.44 m Shock Tube," ARBRL-TR-02503, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, June 1983. (AD A131 894)

The Euler equations for conservation of mass, momentum, and energy per unit volume are solved in differential form for the field variables: density, pressure, temperature, total energy, and a one-dimensional component of flow velocity using finite differencing formulations attributed to Beam[7] and Warming.[8] The ideal gas equation of state, Equation 1, and the Euler equations, Equation 2, are applied to a shock tube,

$$p = (\gamma-1)\ (e-1/2\rho u^2), \tag{1}$$

$$\frac{\partial(\rho A)}{\partial t} + \frac{\partial}{\partial x}(\rho u A) = 0, \tag{2-a}$$

$$\frac{\partial(\rho u A)}{\partial t} + \frac{\partial}{\partial x}[(\rho u^2 + p)A] - p\,\frac{\partial A}{\partial x} = 0, \text{ and} \tag{2-b}$$

$$\frac{\partial(eA)}{\partial t} + \frac{\partial}{\partial x}[uA(e+p)] = 0, \tag{2-c}$$

where p = pressure, γ is the ratio of specific heats, e = total energy/volume, ρ = density, u = flow velocity, A = tube cross-sectional area, t = time, and x = distance.

The initial conditions are non-dimensionalized. Variables at the closed end of the tube, i.e., the compression chamber backwall are computed using image points. Variables of the open end are calculated by using backward differencing.

Independent variables (x,t) are transformed into a computational grid and the governing equations are solved at one-dimensional spacial grid points (x) as a function of time. Refer to Figure 1, a sketch of a computational shock tube. The distribution and total number of grid points are established as computer input parameters. Typically, the number of spacial grid points varies from 100 - 1000 with 400 - 800 providing adequate results.

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[7] R. Beam and R.F. Warming, "An Implicit Factored Scheme for the Compressible Navier-Stokes Equations," AIAA Paper 77-645, 1977.

[8] R.F. Warming and R. Beam, "On the Construction and Application of Implicit Factored Schemes for Conservation Laws," SIAM-AMS Proceedings, Vol. 11, Proceeding of the Symposium on Computational Fluid Mechanics, New York, 1977.

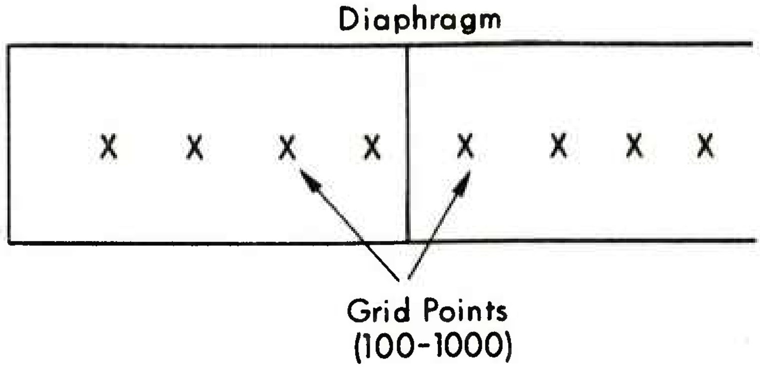


Figure 1. Sketch of a Computational Shock Tube.

The computational grid may be equidistantly partitioned along the tube length or cells may be clustered about a specified location utilizing a hyperbolic function incorporated in the code. Thus, a proportionally large number of grid points may be positioned where cross-sectional area changes occur.

The BRL Q1D computer program treats the opening process of a diaphragm/blast valve as instantaneous. This implies the diaphragm/blast valve separating two compartments of the tube opens instantaneously, and at that moment a shock front is formed with a finite strength which is determined by initial conditions. However, as described before, the real opening process takes a finite amount of time. In order to simulate this condition, the BRL Q1D code was modified so that the diaphragm/blast valve was represented by a parabolic area contraction that linearly opened in time.

The valve opening was modeled by assuming that the smallest throat area is a linear function of time. This is an approximation to the actual opening function for a diaphragm as reported by Rothkopf and Low.[3] A literature search did not reveal any opening functions reported for blast valves, therefore a linear opening function was assumed to be acceptable. It seemed judicious to model the two devices in the same manner to reduce the analytical formulation and the computational coding changes for the BRL Q1D code. The analytical formulation for the coding changes is presented in Appendix A.

In the computer simulation, the time dependent opening of the parabolic area contraction causes continuous compression waves to emanate from the diaphragm/blast valve during the opening process. These compression waves accelerate and coalesce so that the shock front eventually attains a maximum shock velocity at some distance down the shock tube, similar to the experimental situation. The formation distance is then discerned from Pressure-distance profiles and Pressure-time histories. As a check on the computational model, comparisons are made between shock formation distances reported in an experiment on diaphragm opening processes and the distances generated by the modified hydrocode with the experimental conditions as input.

Experimental work on diaphragm opening processes and shock formation distances has been published in a number of articles.[2-5] Of these papers, "Effect on Shock Trajectory of the Opening Time of Diaphragms in a Shock Tube" by Simpson et. al.[2] was chosen to provide experimental data for comparison with the modified BRL Q1D code. This reference was chosen because a thorough investigation of diaphragm effects was made for a variety of operating conditions.

The experimental study was conducted in a shock tube with a rectangular low pressure section of internal dimensions 5.1 by 7.6 cm, and length 3.7 m and a high pressure section of 10.8 cm internal diameter and length 1.9 m, followed by a 15 cm long shape-change section. Driver gas with pressures ranging from 3 to 140 atm and a rectangular diaphragm aperture (5.1 x 7.6 cm) with diagonally scribed diaphragms of aluminum, copper, brass, and nickel were used. The opening time was obtained by measuring the time interval between breaking a wire across the diaphragm and subsequent contact of a petal with the shock tube or by observing the intensity of light transmitted through the diaphragm during the opening process.

After measuring a large number of shock trajectories, Simpson et. al. concluded that the distance (X_f) to the maximum shock velocity (S_m) depends upon the diaphragm opening time (t_o) according to the following expression:

$$X_f = K\, S_m\, t_o, \qquad \text{where } K \approx 2.$$

Figure 2 graphically presents this result. As mentioned previously, a comparison is made between the shock formation distances reported in this experiment and the distances generated by the modified hydrocode. This comparison is presented in the Results section.

B. <u>Blast Valve Modeling for the Large Shock Tube at Centre d'Etudes de Gramat.</u>

The suitability of using a blast valve to replace diaphragm-breaking was computationally determined for a 1-dimensional model (Figure 3) of the large shock tube at the Centre d'Etudes de Gramat (CEG), Gramat, France. The CEG shock tube's rarefaction wave eliminator was not computationally modeled. Instead a sufficiently long driven section was used so that reflected rarefaction waves from the open end did not affect the shock formation process.

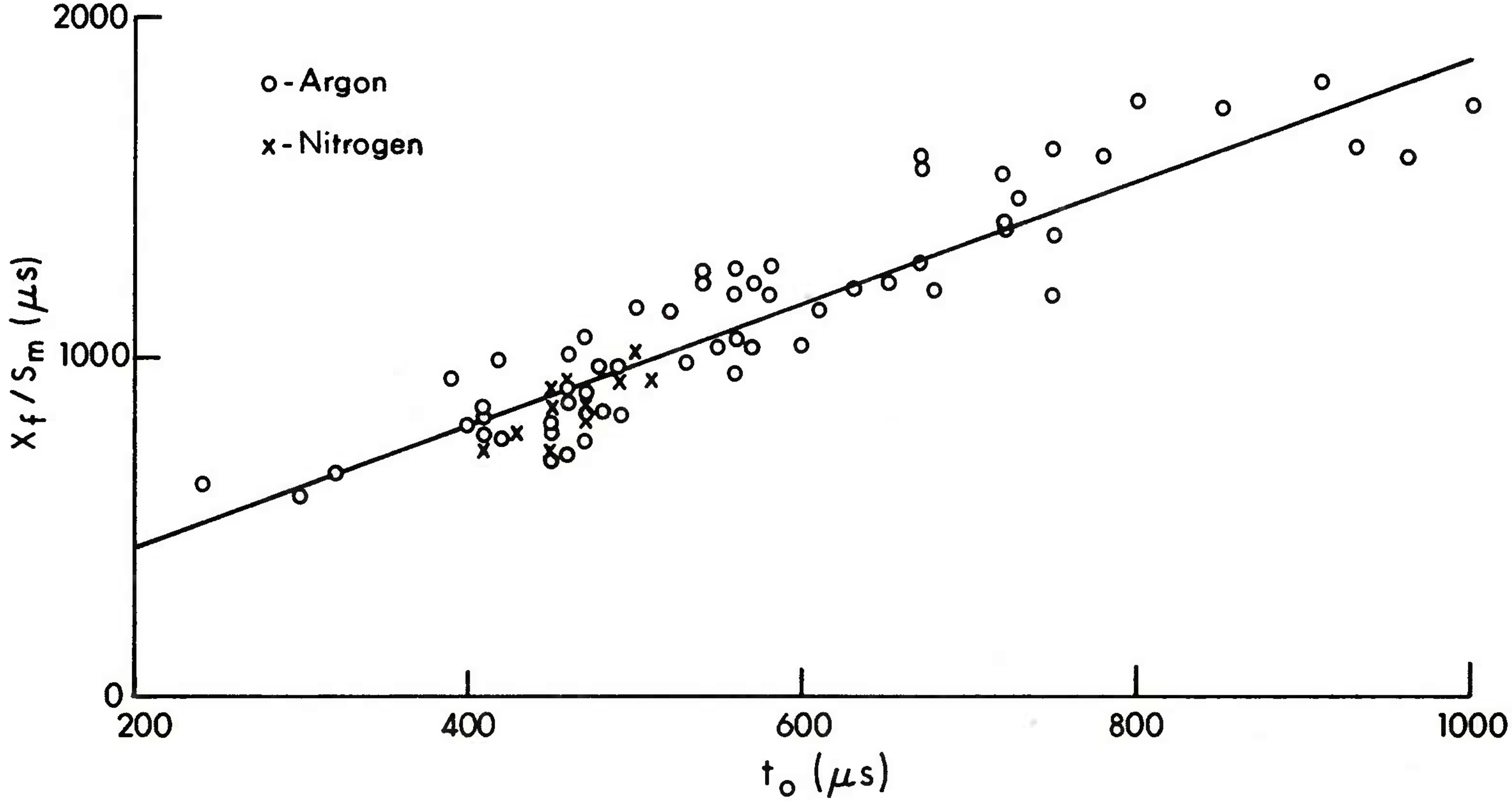
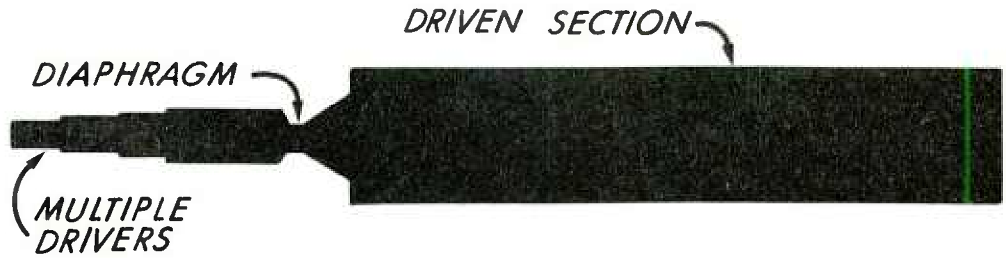


Figure 2. Plot of the Variation of the Period of Shock Acceleration with Diaphragm Opening Time.



1-D COMPUTATIONAL MODEL

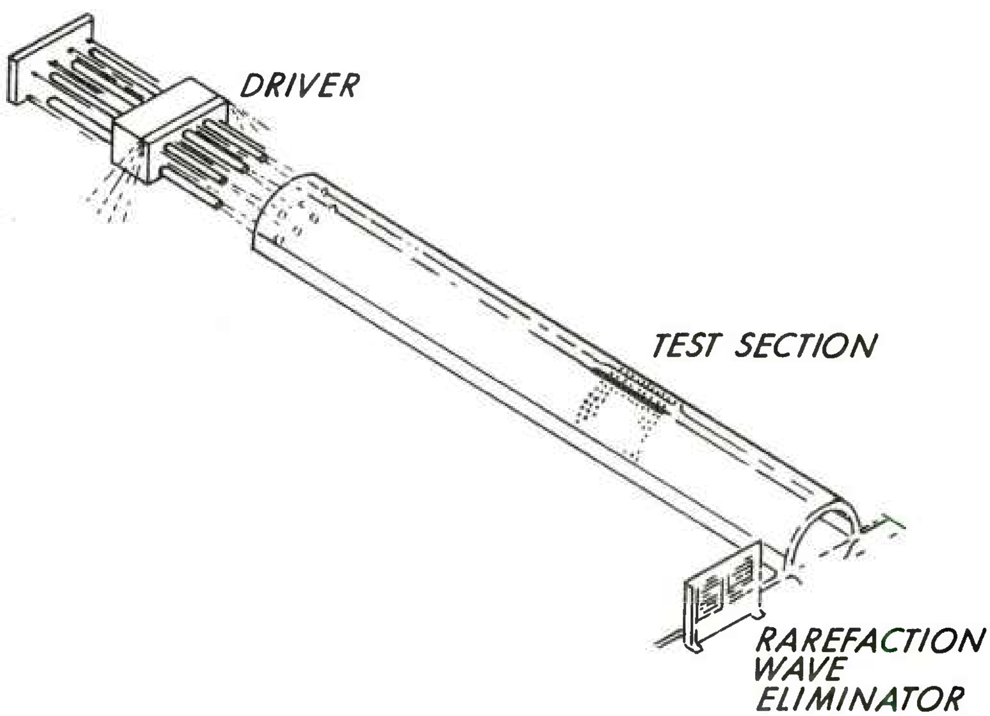


Figure 3. Blast Simulator at Gramat, France; Experimental and Computational Model.

This particular configuration is of interest because BRL is currently considering the feasibility of constructing a large blast thermal simulator (LB/TS) in the United States. The LB/TS will simulate blast loading on either full scale targets or large scaled models. The large shock tube at the Centre d'Etudes de Gramat was built for this type of work.[9-11] Thus, BRL is using the CEG facility as a prototype for the LB/TS, while considering modifications such as thermal capabilities and a larger cross-sectional area driven section. The CEG facility utilizes large diaphragms (≈2' diameter), however, because of the diaphragm problems described in the introduction, a blast valve is another modification under consideration for the LB/TS.

The CEG shock tube dimensions were used as input to the 1-D computational diaphragm/blast valve model. Shock formations for a 235 kPa (34 psi) and a 29.5 kPa (4.3 psi) overpressure (excess pressure over ambient) shock and various valve opening times were examined from pressure-time histories. The main purpose of this phase of the study was to determine the effect of blast valve opening times on the incident shock before its arrival at test station 7 for the above operating conditions. Station 7 is located seven driven section diameters downstream from the end of the diverging nozzle and is the primary testing station for the CEG facility and the proposed LB/TS.

III. RESULTS AND DISCUSSION

A. Comparison of Computational Blast Valve Modeling to Experimental Results.

Initial conditions obtained from experimental shock tube runs by Simpson et. al.[2] were used as input to the modified BRL Q1D code. The initial conditions and resulting code-generated shock formation distances are shown in Table 1. From this data, Figure 2 was amended as shown in Figure 4. Figure 4 provides a graphical representation of shock formation distances versus diaphragm opening times. The experimental data are shown as well as the values obtained from the 1-dimensional computational diaphragm/blast valve runs. Comparison of the experimental and computational data indicates good agreement.

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[9] J.R. Crosnier and J.B. Monzac, "Large Diameter High Performance Blast Simulator," Proceedings of the Fifth International Symposium on Military Applications of Blast Simulation, Stockholm, Sweden, May 23-26, 1977.

[10] J.R. Crosnier, S. Gratias, J.B. Monzac, and H. Richard, "Concepts and Design for a Large Diameter High Performance Blast Simulator," Proceedings of the Fourth International Symposium on Military Applications of Blast Simulation, Southend-on-Sea, England, September 9-12, 1974.

[11] H.-O. Amann, "Theoretical and Experimental Investigations for the Driving Mechanism of a Large-Diameter Shock Tube," Proceedings of the Fourth International Symposium on Military Applications of Blast Simulation, Southend-on-Sea, England, September 9-12, 1974.

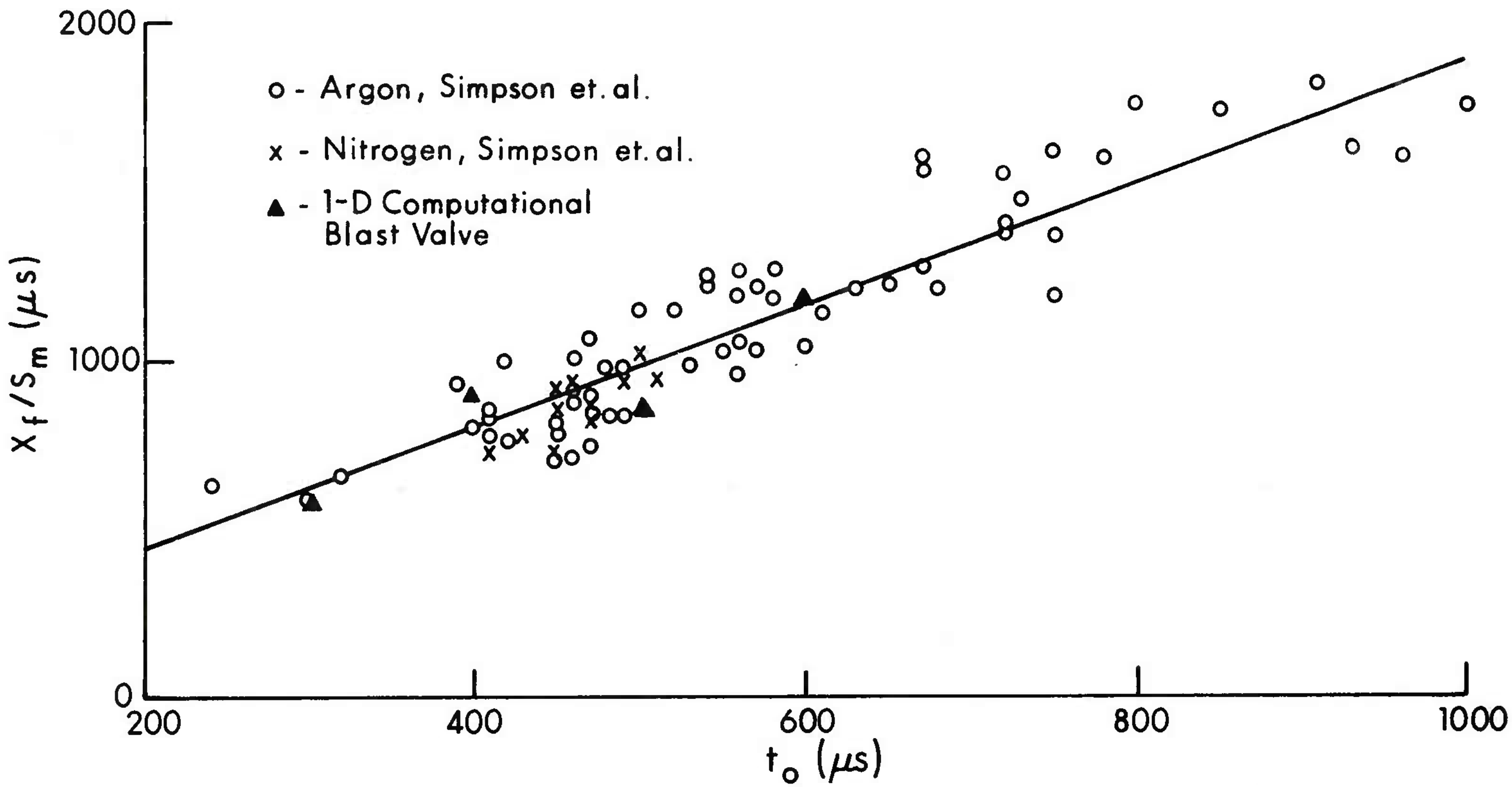

Figure 4. Amended Plot of the Variation of the Period of Shock Acceleration with Diaphragm Opening Time.

Table 1. Initial Conditions and Shock Formation Distance for Simpson et al. Shock Tube Configuration.

P_1 (psi)	t_{op} (μs)	$\frac{P_4}{P_1}$	X_f (m)	$\frac{X_f}{S}$ (s)
400	300	27.2	.372	.0006
223	400	15.15	.543	.0009
138.5	500	9.42	.52	.0009
100	600	6.80	.686	.0012

Therefore, the 1-dimensional computational diaphragm/blast valve model appears to satisfactorily model the opening process and subsequent shock acceleration for diaphragms and blast valves.

B. Results of Blast Valve Modeling for Centre d'Etudes de Gramat Shock Tube Configuration.

Figure 5 displays experimental and computational data for the 1-D CEG shock tube. Distance to maximum shock velocity is plotted against blast valve opening times. The straight lines represent the expression $X_f = 2\ S_m\ t_o$ for a 34.47 kPa (5 psi) overpressure waveform ($S_m \simeq 593$ m/s) and for a 241.32 kPa (35 psi) overpressure waveform ($S_m \simeq 387$ m/s). Simpson et. al.[2] formulated this expression from experiments as a guide for predicting shock formation distances in a straight driven section. Of course, the driven section of the CEG shock tube is "non-straight," therefore these lines are only included as a reference.

In Figure 5, the x's and o's represent shock formation distances measured from the diaphragm. The x represents valve opening times and distances where the incident shock was considered unacceptable from pressure-time histories while the o represents opening times and distances where the incident shock was acceptable. The primary shock is considered acceptable if the overpressure and the time of arrival of the peak are within 15% of their final valves and if the incident's shock's rise time is increased no more than 8 ms over the rise time computed for an instantaneous blast valve opening. In the BRL Q1D code, artificial viscosity coupled with grid spacing computationally smears shocks. Thus, the rise times computed for the instantaneous blast valve openings are not real but are the result of the code's inability to model discontinuous shocks.

To illustrate the acceptability criterion for a shock, Figure 6 shows pressure-time histories at various test stations in the tube for a 235 kPa (34 psi) overpressure shock and a blast valve opening time of .05 s. The waveforms typically show a sharp pressure increase early in time, the primary shock, a decaying pressure region caused by rarefaction waves from the drivers, and sometimes a sharp pressure decrease later in time, a backward facing shock. The backward facing shock originates from the overexpanded diverging nozzle, and is sometimes swept downstream as a result of the low back pressures in the driven section. In Figure 6 one notes the shock is not acceptable at x stations located at 33 m and 65.2 m, but is acceptable for an x station located 75.8 m downstream of the blast valve.

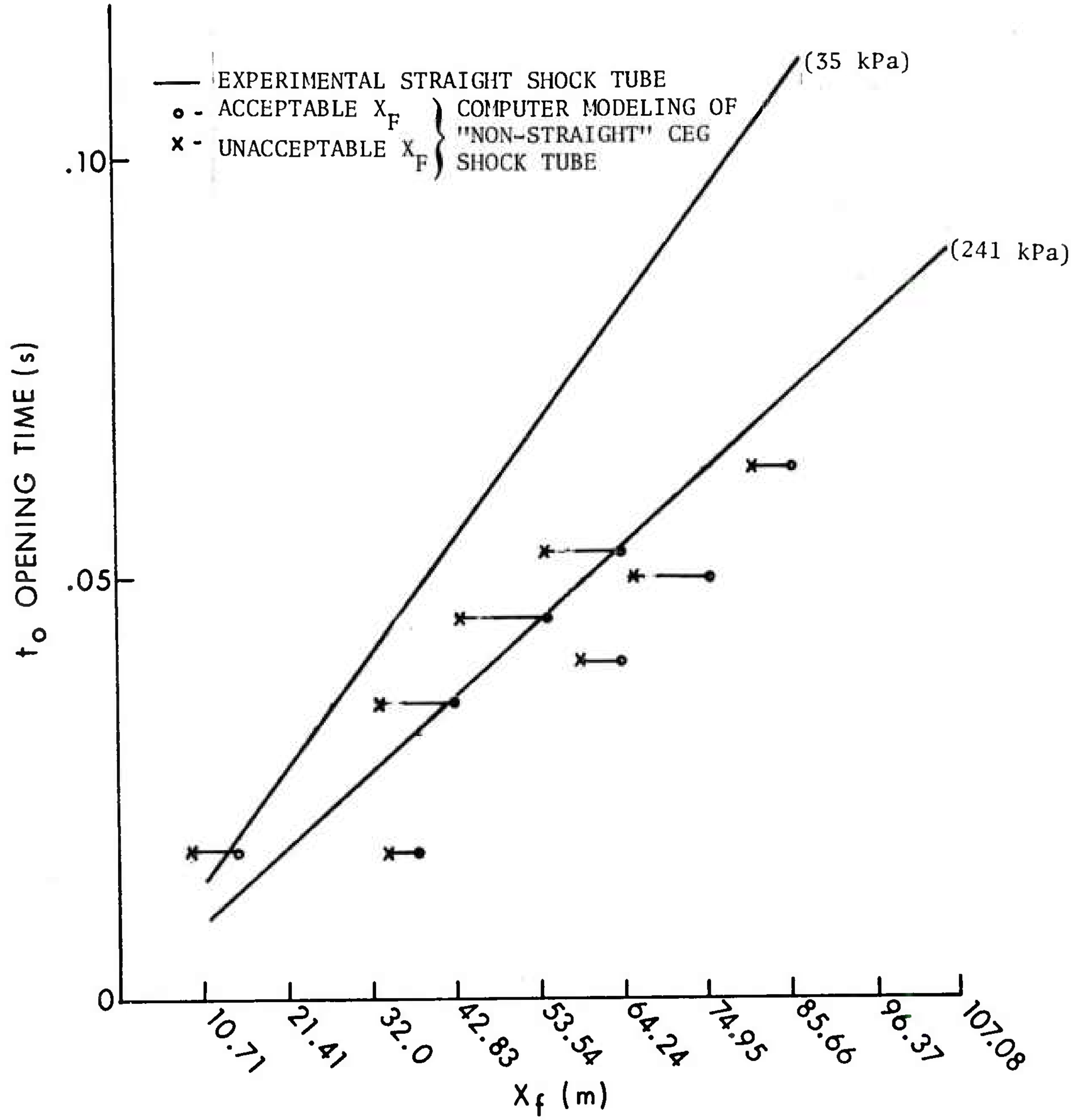

Figure 5. Distance to Maximum Shock Velocity Versus Blast Valve Opening Times.

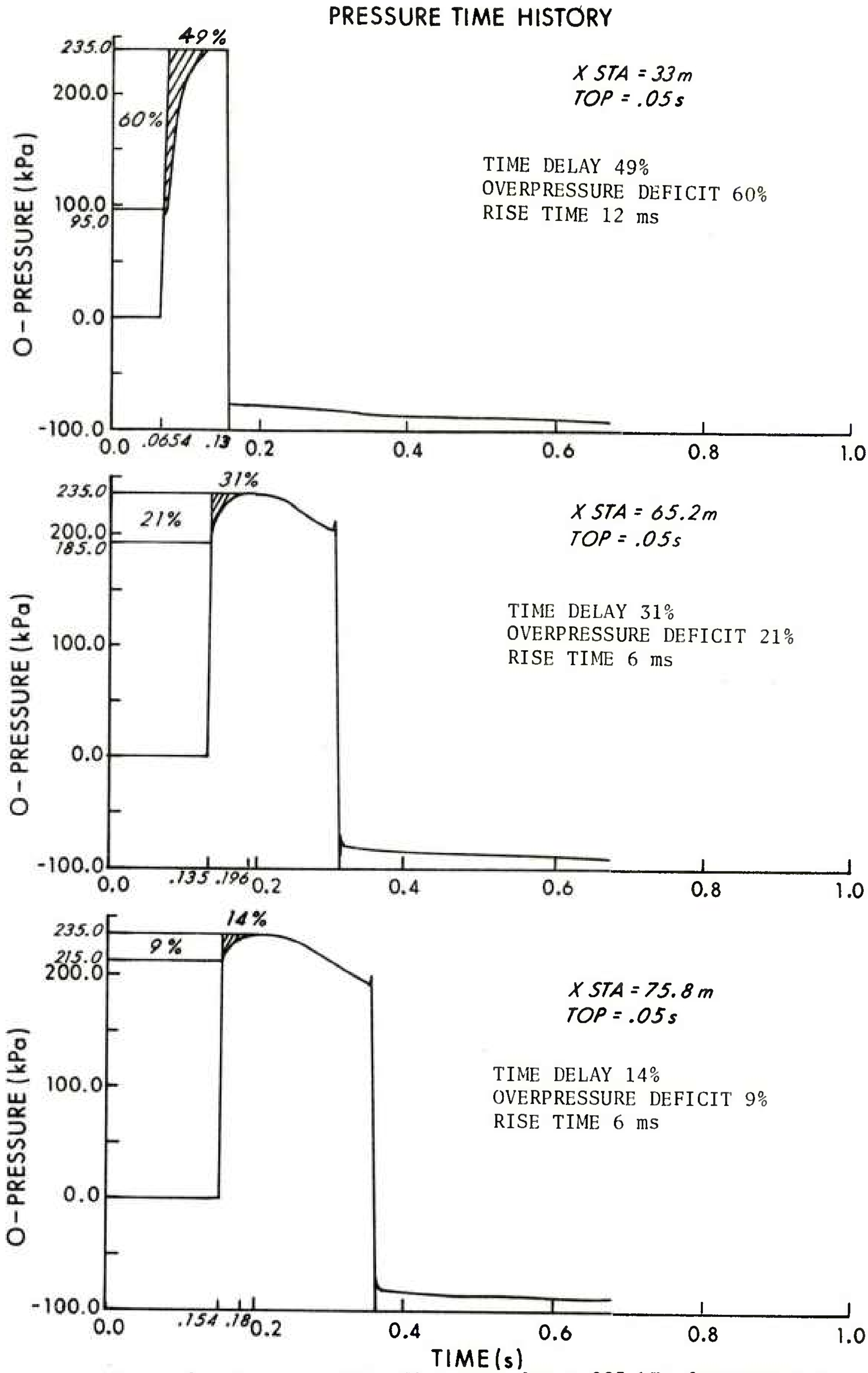

Figure 6. Pressure-Time Histories for a 235 kPa Overpressure Shock at Various X Stations and a Blast Valve Opening Time of .05 s.

Furthermore, Figure 7 shows pressure-time histories for a 235 kPa (34 psi) overpressure shock at x station at 75.8 m for a nearly instantaneous valve opening time (top = .0035) and a very long valve opening time (top = .105). Comparing these to x station at 75.8 m for a valve opening time of .05 s, Figure 5, one notices that there is very little difference between the nearly instantaneous valve opening time waveform and the .05 s valve opening time waveform. The shock is considered acceptable in both cases. However, above 0.5 s, waveforms more similar to the .10 s valve opening time P-t history are obtained at x station at 75.8 m. These waveforms show a compression wave passing the x station. Although, this condition might be desirable for some simulation purposes (such as the precursor of a nuclear shock), it is not desirable for a shock simulator.

Figures 8 and 9 present pressure-time histories for a 29.5 kPa (4.3 psi) overpressure shock at various x stations and for various blast valve opening times. From Figure 8, one notes an acceptable waveform occurs at 65 meters for a blast valve opening time of 52.5 ms. Consulting Figure 5, it is reasonable to predict a well formed 29.5 kPa overpressure shock before test station 7 (75.8 m downstream) for blast valve opening times less than approximately 55 ms.

Figure 9 presents pressure-time histories for a 29.5 kPa (4.3 psi) overpressure shock at x station equal to 75.8 m for various blast valve opening times. Note that for a blast valve opening time of .07s, the shock is no longer acceptable. For a blast valve opening time of .0354s the shock is nearly identical to the shock produced by an instantaneous blast valve opening except for the rise time of 7 ms. The rise time for the instantaneous case is 5 ms. The waveform has obtained a spike that effectively increases the peak overpressure from 29.5 kPa to 34 kPa.

For similar initial conditions, a spike is also observed experimentally, therefore it is a real phenomenon that occurs with the CEG facility. However, the spike is undesirable because it unsatisfactorily alters the waveform. The waveform is meant to represent the ideal, classical exponentially decaying wave that results from a surface burst.[12] Figures 8 and 9 show that an acceptable shock can be produced for a 29.5 kPa overpressure shock without a spike if one opens the blast valve slowly enough.

Referring to Figure 5 again, the x's and o's represent the accumulation of the acceptable and unacceptable shock formation distances from the pressure-time histories. In order to obtain acceptable shock formations less than 75 meters (the distance to the primary testing station), Figure 5 shows for the 29.5 to 235 kPa (4.3 to 34 psi) overpressure range that the blast valve opening times must be less than approximately 50 milliseconds.

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[12] A. Mark, "Numerical Simulation of the Gas Dynamic Cycle of Complex, Large-Scale Shock Tubes," Transactions of the Twenty-Seventh Conference of Army Mathematicians, ARO Report 82-1.

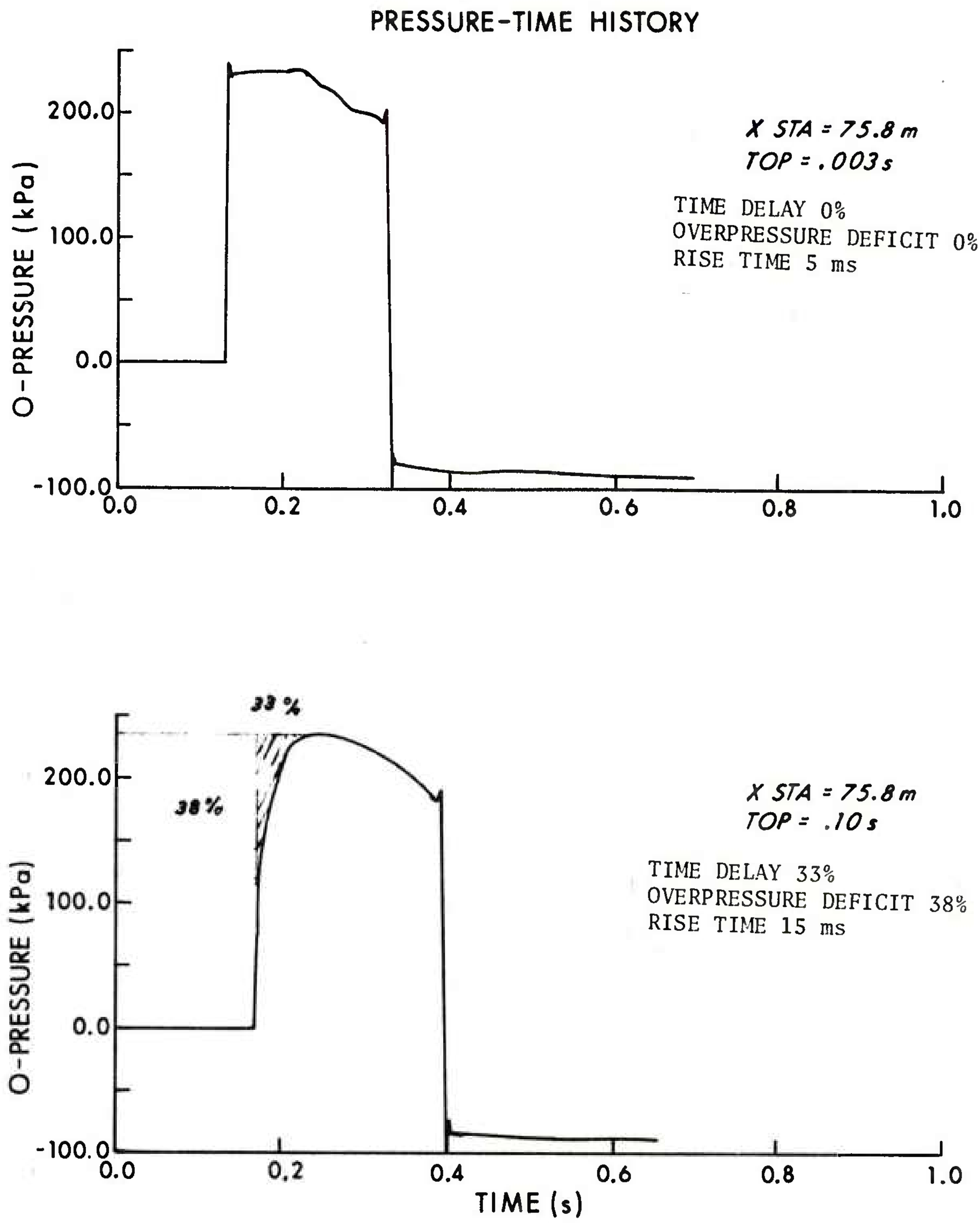

Figure 7. Pressure-Time Histories for a 235 kPa Overpressure Shcok at X Station 75.8 m and Blast Valve Opening Times of .003 s and .10 s.

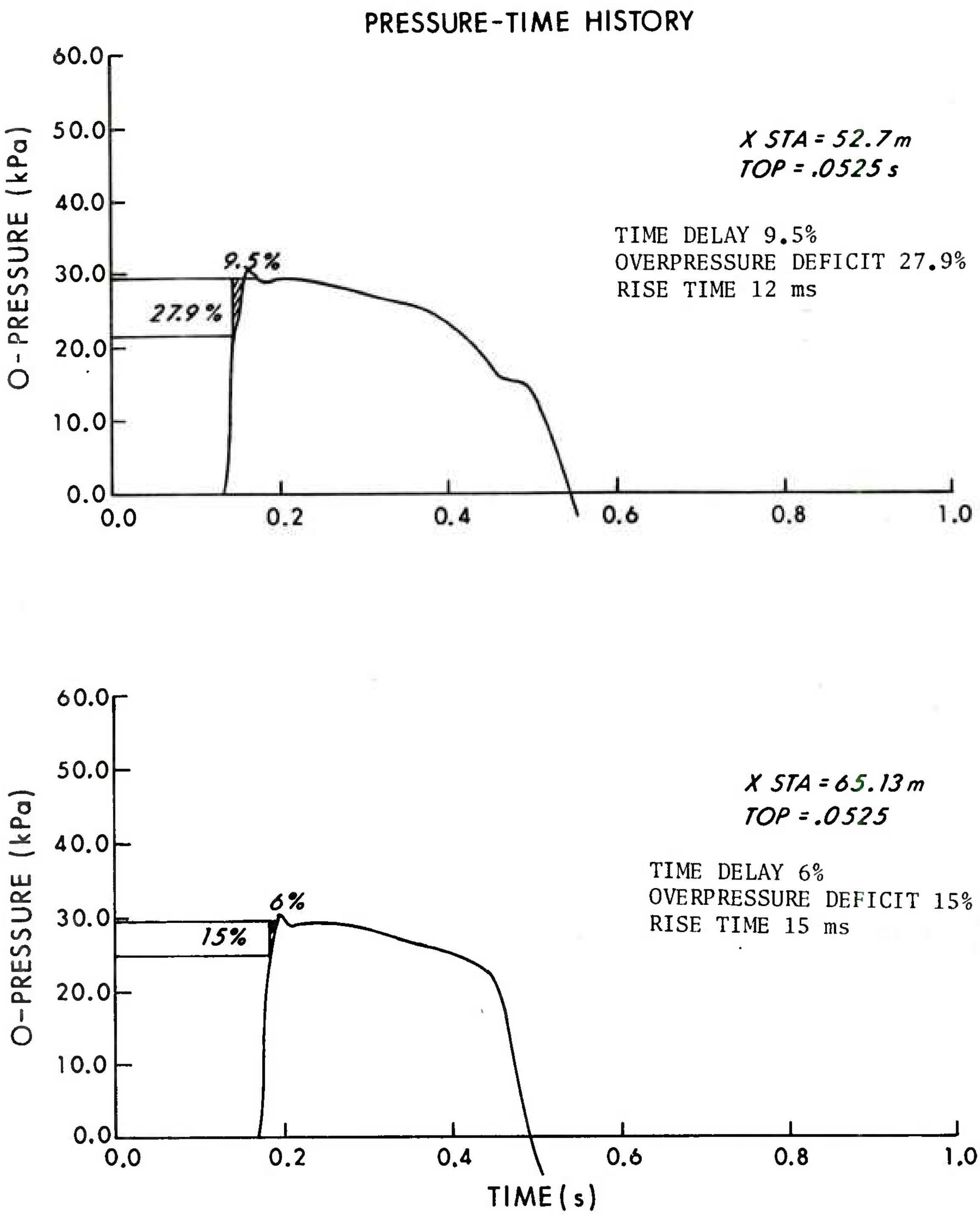

Figure 8. Pressure-Time Histories for a 29.5 kPa Overpressure Shock at X Stations 52.7 m and 65.13 m and a Blast Valve Opening Time of .0525 s.

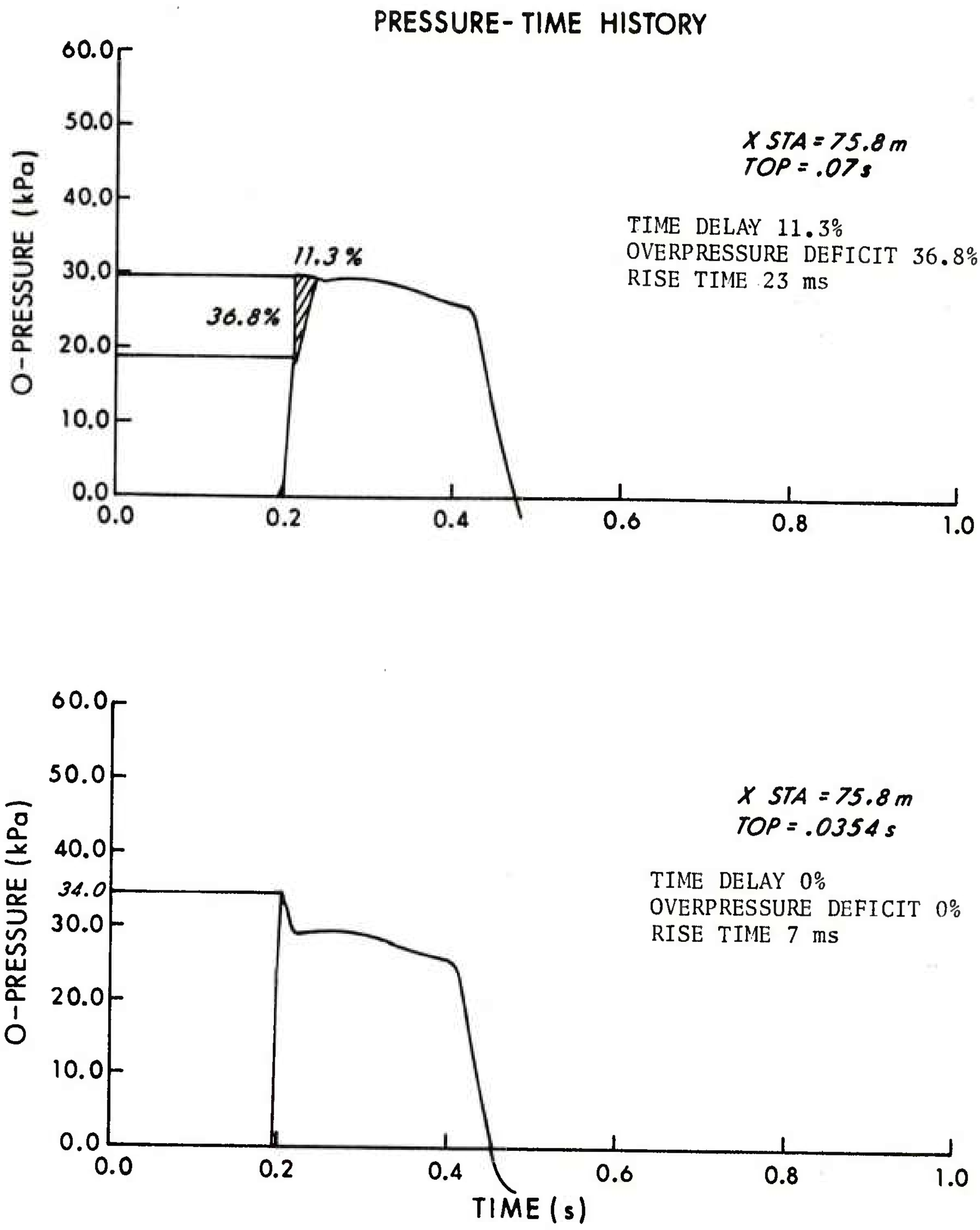

Figure 9. Pressure-Time Histories for a 29.5 kPa Overpressure Shock at X Station 75.8 m and Blast Valve Opening Times of .07 s and .0354 s.

IV. CONCLUSIONS

This report examined the possiblity of using a fast acting (blast) valve to replace diaphragm breaking in a shock tube. This was accomplished by successfully modeling the diaphragm/blast valve opening process with a modified verison of the BRL Q1D code. The computational diaphragm/blast valve model was in satisfactory agreement with experimental data.

For the one dimensional model of the Centre d' Etudes de Gramat shock tube, it was determined with the computational diaphragm/blast valve model that a blast valve which opens in less than 50 milliseconds approximates shocks within these limitations;

a) Peak overpressure is within 15% of its final value

b) Time of arrival of peak is within 15% of its final value

c) Rise time of incident shock is increased no more than 8 ms from the instantaneous case.

A shock with these characteristics is acceptable for simulating shock/target interactions where the primary damage mechanism is overturning or whole-body displacement through drag loading. A blast valve which opens in less than 50 milliseconds should produce a shock meeting the above criterion before the primary testing station located 75 meters downstream.

A continuation of this study is needed to determine the blast valve opening times required to produce a simulated blast wave with a fully formed discontinuous shock front. Such a blast wave is required for producing the maximum loading on targets during the initial diffraction loading period.

An assumption made for this blast valve study was an area opening function that was linear in time. Therefore, another continuation of this study might address different blast valve opening functions, possibly even opening functions for real blast valves, if the data can be obtained.

Also, an unexpected result of this blast valve study was the observation that for lower pressure shots, a blast valve that opens slowly enough will degrade the spikes that are present computationally and experimentally in the pressure-time histories. The problem then is to find such a blast valve opening time and driver pressure ratio combination for which the spike is degraded, but the desired overpressure peak is retained. The BRL Q1D code provides the capability of doing such a parametric study at relatively little cost.

REFERENCES

1. Private Communication from Dr. Fritz Oertel, Ballistic Research Laboratory, May 1983.

2. C.J.S.M. Simpson, T.R.D. Chandler, and K.B. Bridgman, "Effect on Shock Trajectory of the Opening Time of Diaphragms in a Shock Tube," Phys. Fluids, Vol. 10, No. 9, September 1967, pp. 1894-1896.

3. E.M. Rothkopf and W. Low, "Diaphragm Opening Process in Shock Tubes," Phys. Fluids, Vol. 17, No. 6, June 1974, pp. 1169-1172.

4. F.L. Curzon and M.G.R. Phillips, "Low Attenuation Shock Tube: Driving Mechanism and Diaphragm Characteristics," Canadian Journal of Physics, Vol. 49, 1982, pp. 1982-1993.

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6. G.A. Coulter, G. Bulmarsh, and C.N. Kingery, "Experimental and Computational Modeling of Rarefaction Wave Eliminators Suitable for the BRL 2.44 m Shock Tube," ARBRL-TR-02503, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, June 1983. (AD A131 894)

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8. R.F. Warming and R. Beam, "On the Construction and Application of Implicit Factored Schemes for Conservation Laws," SIAM-AMS Proceedings, Vol. 11, Proceeding of the Symposium on Computational Fluid Mechanics, New York, 1977.

9. J.R. Crosnier and J.B. Monzac, "Large Diameter High Performance Blast Simulator," Proceedings of the Fifth International Symposium on Military Applications of Blast Simulation, Stockholm, Sweden, May 23-26, 1977.

10. J.R. Crosnier, S. Gratias, J.B. Monzac, and H. Richard, "Concepts and Design for a Large Diameter High Performance Blast Simulator," Proceedings of the Fourth International Symposium on Military Applications of Blast Simulation, Southend-on-Sea, England, September 9-12, 1974.

11. H.-O. Amann, "Theoretical and Experimental Investigations for the Driving Mechanism of a Large-Diameter Shock Tube," Proceedings of the Fourth International Symposium on Military Applications of Blast Simulation, Southend-on-Sea, England, September 9-12, 1974.

12. A. Mark, "Numerical Simulation of the Gas Dynamic Cycle of Complex, Large-Scale Shock Tubes," Transactions of the Twenty-Seventh Conference of Army Mathematicians, ARO Report 82-1.

Appendix A
Analytical Formulation of Diaphragm/Valve Opening

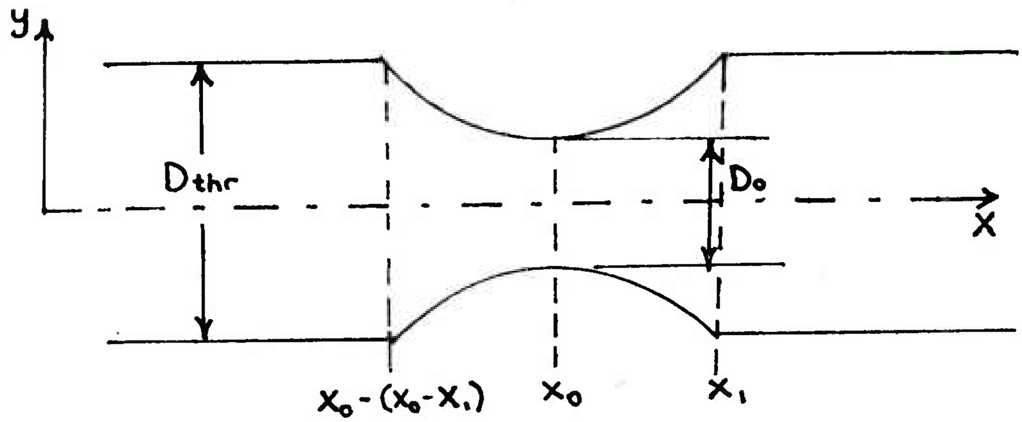

Figure A-1. Table Diameter in Throat Area.

The diameter in the throat area is

$$d(x) = 2y(x)$$

where

$$y(x) = \begin{cases} \frac{1}{2} D_o + \frac{1}{2}(D_{thr} - D_o)\left(\frac{x-x_o}{x_1-x_o}\right)^2 & \text{of } |x-x_o| < |x_1-x_o| \\ \frac{1}{2} D_t & \text{of } |x-x_o| \geq |x_1-x_o| \end{cases}$$

Throat area for arbitrary reference diameter D_1:

$$\frac{A(x)}{A_1} = \frac{d^2(x)}{D_1^{\,2}} = \begin{cases} \left[\frac{D_o}{D_1} + \left(\frac{D_{thr}}{D_1} - \frac{D_o}{D_1}\right)\left(\frac{x-x_o}{x_1-x_o}\right)^2\right]^2 & \text{of } |x-x_o| < |x_1-x_o| \\ \left(\frac{D_{thr}}{D_1}\right)^2 & \text{of } |x-x_o| \geq |x_1-x_o| \end{cases}$$

The opening process is modeled by making D_o the following function of time:

$$D_o(t) = \left[D_{o\ initial}^{\,2} + \frac{t - t_{initial}}{t_{final} - t_{initial}}\left(D_{o\ final}^{\,2} - D_{o\ initial}^{\,2}\right)\right]^{\frac{1}{2}}$$

Where $D_{o\ initial} \neq 0$

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